Note on Resonances in Transmutations of Light Nuclei

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It is shown that the sharp resonance effects observed in many transmutations involving light nuclei require the existence of fairly strict selection rules to limit the decay rates of the corresponding compound nuclei. Such selection rules in several cases follow from the slowness of the interconversion of spin and orbital angular momentum. Some consequences of this are discussed for the bombardment of B and F by protons.

When light nuclei are bombarded with protons, the transmutation functions for the various alternative reactions are often radically different. This suggests that, by bombardment of a given nucleus, compound nuclei can be formed which have quite different properties. Thus in the reaction

$$Li^7+H^1\rightarrow(Be_A{}^8)\rightarrow 2He^4 \qquad (1a)$$

the yield of 8 cm α-particles increases steadily with bombarding voltage, and for low energies, where such considerations are applicable, follows the course expected from the arguments of Gamow on the penetration of the potential barrier by the proton. On the other hand the reaction in which high energy γ-rays are emitted,

$$Li^7+H^1\rightarrow(Be_B{}^8)\rightarrow Be^8+\gamma, \qquad (1b)$$

exhibits a pronounced and sharp resonance at a bombarding energy of 440 kv.[1]

With the proton bombardment of fluorine, the situation is similar but a little more complicated. Here too the 6 cm α-particle yield from the reaction

$$F^{19}+H^1\rightarrow(Ne_A{}^{20})\rightarrow O^{16}+He^4 \qquad (2a)$$

increases rapidly with bombarding energy,[2] but the γ-ray transmutation function[1] shows sharp resonances of increasing magnitude at 330 kv, 890 kv, 940 kv. Two reactions have been proposed to account for these γ-rays,

$$F^{19}+H^1\rightarrow(Ne_B{}^{20})\rightarrow(O_B{}^{16})+He^4 \rightarrow O^{16}+He^4+\gamma \qquad (2b)$$

$$F^{19}+H^1\rightarrow(Ne_B{}^{20})\rightarrow(Ne_C{}^{20})+\gamma \rightarrow\begin{cases}O^{16}+He^4+\gamma\\ Ne^{20}+\gamma+\gamma'\end{cases} \qquad (2b')$$

where again the parentheses indicate excited nuclei. At least for low bombarding energies the γ-rays are approximately monochromatic,[3] with an energy $\sim$6 Mev; the excitation energy of the $Ne_B{}^{20}$ is more than twice this.

Still more complicated is the bombardment of B^{11} with protons. Here most of the α-particles are to be ascribed[4] to the reaction

$$B^{11}+H^1\rightarrow(C_A{}^{12})\rightarrow(Be_A{}^8)+He^4\rightarrow 3He^4, \qquad (3a)$$

where the $Be_A{}^8$ has an excitation of a few Mev. The yield of these alpha-particles increases smoothly[5] and without marked evidence of resonance for bombarding energies up to 600 kv. On the other hand both the reactions

$$B^{11}+H^1\rightarrow(C_B{}^{12})\rightarrow Be^8+He^4 \qquad (3b)$$

$$B^{11}+H^1\rightarrow(C_B{}^{12})\rightarrow C^{12}+\gamma \qquad (3b')$$

show[5, 6] sharp resonance at 180 kv. The yield of γ-rays increases again markedly[7] at about 700 kv, suggesting the existence of a further resonance level in this neighborhood.

Since in any case the sharpness of resonance is a measure of the lifetime of the compound nucleus formed by the capture of the bombarding particle, the compound nuclei $Be_B{}^8$, $Ne_B{}^{20}$, $C_B{}^{12}$ must differ very radically from $Be_A{}^8$, $Ne_A{}^{20}$, $C_A{}^{12}$ as to their possibilities and rates of disintegration. Now in each of the cases we are considering,

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[1] Hafstad, Heydenburg and Tuve, Phys. Rev. **50**, 504 (1936).
[2] Henderson, Livingston and Lawrence, Phys. Rev. **46**, 38 (1934).
[3] Delsasso, Fowler and Lauritsen, Phys. Rev. **51**, 527, (1937).
[4] Dee and Gilbert, Proc. Roy. Soc. **154**, 279 (1936).
[5] Williams, Wells, Tate and Hill, Phys. Rev. **51**, 434 (1937).
[6] Bothe and Gentner, Zeits. f. Physik **104**, 685 (1937).
[7] Fowler and Lauritsen, private communication.

there are just three energetically possible modes of disintegration:

(1) Reemission of the bombarding proton, with decay constant $\Gamma_p/\hbar$,
(2) emission of an α-particle, $\Gamma_\alpha/\hbar$,
(3) γ-radiation, $\Gamma_\gamma/\hbar$.

The decay constant of the compound nucleus will be just $\Gamma/\hbar=(\Gamma_p+\Gamma_\alpha+\Gamma_\gamma)/\hbar$. The absence of marked resonance effects for the A-reactions shows that Γ must be very large for the A nuclei; Γ_γ is always small, and Γ_p is surely small for low bombarding energies because of the effect of the barrier. Under these circumstances $\Gamma\sim\Gamma_\alpha$, $\Gamma_\alpha\gg\Gamma_\gamma$, $\Gamma_\alpha\gg\Gamma_p$. Thus the sharp resonances observed for the B-reactions show that the B nuclei can disintegrate by α-emission, either not at all, or very much more slowly than the A nuclei. The reaction (3b) shows that in this case at least we have to do with retarded but not forbidden α-decay. What is then the distinction between the A and B nuclei which brings about this great difference in behavior?

For the case of $Be_B{}^8$, a satisfactory answer to this question has already been given,[1] for since two unexcited α-particles are necessarily described by a wave function which is even with respect to the mirroring of the coordinates of all particles in the center of mass, a state of Be^8 will not be able to decay into two such α-particles at all if it is odd; we thus account qualitatively for the facts if we say that $Be_A{}^8$ is even, $Be_B{}^8$ odd. Analogous considerations of parity are however inapplicable to C^{12} and Ne^{20}, since the disintegration products are not in these cases identical nuclei. It is true that arguments of parity may demand that the α-particle come off with a relative angular momentum different from zero; but the energy of the α-particle is so high that this will not alter the order of magnitude of the decay constant. We have thus to ask what other selection rule can so markedly reduce the α-decay rate of the two nuclei $C_B{}^{12}$, $Ne_B{}^{20}$.

Now there is one feature of nuclear forces which follows quite generally from the fact that the velocities of neutrons and protons are small compared to c, that we have here an essentially nonrelativistic problem. This is that the total spin S of the neutrons and protons, and their total orbital angular momentum L, will vary only very slowly with time;[7a, 8] for the coupling between them which is responsible for their variation is of the order $(v/c)^2$, and corresponds, according to the suggestion of Inglis,[9] merely to the Thomas precession of the spins in accelerated motion $(\omega_T=-(\mathbf{v}\times\dot{\mathbf{v}})/2c^2)$. Thus the ideas of Bohr on the ease of energy exchange between particles, and the fact that nuclear forces surely do depend upon the relative spin orientations of the particles, guarantee a rapid exchange on the one hand of the orbital angular momentum among the particles composing the nucleus, and on the other of the individual particle spins, but do not in any way alter the approximate constancy of S and L. In fact, since the rate of conversion of spin into orbital angular momentum should be proportional to the square of the coupling energy, this conversion should take a time larger than the nucleus collision time by a factor of the order $(c/v)^4\sim10^4$.[10]

Now for the α-particle certainly $S=0$. Moreover, for the product nuclei Be^8, O^{16} one would expect from very general symmetry arguments that the lowest states would have paired neutron and proton spins and $S=0$. Thus the normal α-decay products will have vanishing spin, and only when the intermediate nucleus too has $S=0$ will this normal α-decay be rapid; for compound nuclei with $S\neq0$, the possibility of such decay will depend on the interconversion of spin and orbital angular momentum, the decay time will in any case be increased by a factor $(c/v)^4$, and marked resonance effects will appear. The absence of such resonance for the A nuclei shows that for them $S=0$; thus normal F^{19} and B^{11} must have $S=\frac{1}{2}$, as indeed one would expect. We then wish to suggest that $Ne_B{}^{20}$, $C_B{}^{12}$ are triplet states, with $S=1$. More generally, it

[7a] L and S would be constants of the motion for any nuclear Hamiltonian which is invariant under a rotation of the positional coordinates of all particles alone, and of their spins alone. This condition is satisfied for all the types of forces commonly considered in nonrelativistic nuclear theory (Majorana, Heisenberg, Wigner, Bartlett forces).

[8] The importance of the approximate constancy of S for the interpretation of nuclear reactions was first recognized by Goldhaber, Proc. Camb. Phil. Soc. **30**, 361 (1934).

[9] D. R. Inglis, Phys. Rev. **50**, 783 (1936).

[10] This selection rule applies only to the interconversion of spin and orbital momentum; in γ-ray emission, where magnetic dipole radiation can alter the spin, and probably in β-ray emission, transitions involving a change of S by one unit are hardly less probable than those leaving it unaltered.

seems not unlikely that for nuclei of odd atomic weight the normal states will have $S=\frac{1}{2}$, so that when these are bombarded by protons or neutrons, only singlet and triplet states of the compound nucleus will be formed. If states of even higher multiplicity were formed in such reactions, they would be almost stable against normal α-decay.

II

We shall now have to see in greater detail whether this explanation is tenable, and what implications it has for the interpretation of the reactions in question.

The Ne^{20} formed by bombarding F^{19} with protons has an excitation energy of more than 12 Mev. We should thus expect the singlet states, which can decay to $O^{16}+He^4$, to have a short lifetime, since the α-particles emitted have so great an energy that the effects of the potential barrier will be negligible.[11] Since, for instance, for the heavier and less highly excited nucleus P^{31} formed from $Al^{27}+He^4$, the breadth of the levels is $\sim 10^5$ v, we would expect for the singlet levels of Ne^{20}, $\Gamma \sim \Gamma_\alpha \sim 10^5-10^6$ v. This breadth is so large that from such states we should surely expect no marked resonance in the yield of long range α-particles.[11] For triplet states of Ne^{20} the long range α-emission will be slowed up by $(c/v)^4$, so that here $\Gamma_\alpha' \sim 100$ v. In order to account on the basis of reaction (2b′) for the fact[12] that the γ-ray yields at ~ 1 Mev are at least ten times the total long range α-particle yield, we should thus have to assume a value of $\Gamma_\gamma \sim 1000$ v. This value is far larger than any which have been found for nuclear γ-rays, and at least 100 times that necessary to account for the far more energetic γ-ray of the simpler nucleus $Be_B{}^8$. Moreover, the fact that the γ-ray spectrum consists only of radiation quite near 6 Mev could on this basis be explained only quite artificially. We are thus led to consider the possibility that O^{16} has triplet states lying about 6 Mev above ground, and that the reaction which successfully competes with the emission of long range α-particles is the emission of slow α-particles, without spin change, but with so low an energy that the level breadth Γ_α'', though larger than Γ_α', is still small enough to give sharp resonances ($100 \text{ v} < \Gamma_\alpha'' < 10{,}000$ v). Experimentally one knows that at bombarding energies ~ 400 kv there are no short range α-particles of energy > 2 Mev emitted;[7] and for this process to compete successfully with the long range α-emission, the energy of the particles cannot be far less than 1.5 Mev. A value in this neighborhood is consistent with the energy balance. If this suggestion is correct, one would expect the ratio $\Gamma_\alpha''/\Gamma_\alpha'$ to increase rapidly with energy; and for the lowest resonance level (~ 330 kv) it would seem possible that some long range α-particles could be observed. The absence of other lines in the γ-ray spectrum could then be interpreted in a natural way because of the absence of low-lying excited states in the "closed shell" nucleus O^{16}.

In the case of the $B^{11}+H^1$ reactions, one will again expect that the Γ_α for C^{12} in singlet states will be large, and that with an increase in bombarding energy the yield in (3a) will increase smoothly with Γ_p. Again one will make a triplet C^{12} responsible for the γ-ray emission and the long range α-particles which show marked resonance. But here there is a point which calls for further explanation: why is the ratio of long to short range α-particles so much smaller for $C_A{}^{12}$ than for $C_B{}^{12}$? Since for the low resonance energy the reaction (3a) is far more probable than (3b), and since the long range α-particles are not isotropically distributed in direction,[13] it seems reasonable to assume that $C_A{}^{12}$ is formed by capture of an s-proton, and is odd, and that $C_B{}^{12}$ is formed by p-capture, and is even. If the normal state of B^{11} were a ^2P state, $C_A{}^{12}$ would then be an odd ^1P state; and $C_B{}^{12}$ an even ^3D state, so that both states could give both α-particle reactions, and one could expect no great difference in the relative yields. If however normal B^{11} is a ^2D, then $C_A{}^{12}$ is an odd ^1D, and this cannot disintegrate into a normal $Be^8(^1S)$ and an unexcited α-particle at all, whereas $C_B{}^{12}$,

[11] Since $\Gamma_\alpha \gg \Gamma_p$, and Γ_α varies slowly with bombarding energy, the interpretation of the rapid rise (faster than Γ_p) of the yield in this reaction given in reference (2) cannot be right. If this more rapid rise should be confirmed, one would have to understand it in terms of a residual structure for the singlet levels, or a contribution from high-lying triplet levels, of the compound nucleus.

[12] E. McMillan, Phys. Rev. **46**, 868 (1934).

[13] Neuert, Physik. Zeits. **38**, 122 (1937).

in an even triplet state can. We wish therefore to suggest this interpretation, which is hardly in serious conflict with the calculations[14] based on a Hartree model, according to which the ^2D of B^{11} is only $\sim 2.5\ mc^2$ higher than the ^2P. According to this view the resonance reaction may contribute also to the short range α-particles, and the small yield from this reaction must be ascribed to the smallness of Γ_p for a p-proton at these low energies.

With the Li reactions, one point remains a little puzzling if one accepts the usual interpretation: since normal Li^7 is almost certainly odd, the long range α-reaction must be ascribed to the capture of a p-proton, the $Be_B{}^8$ to that of an s-proton. The fact that the long range α-reaction comes from p-capture may in part account[15] for the smallness of the α-particle yield compared to that of the reaction $Li^6 + H^1 \rightarrow He^3 + He^4$. One would now expect that if the $Be_A{}^8$ could be formed in a ^1D state, the corresponding α-particles should be distributed in angle with marked anisotropy; and the fact that the observed distribution[16] seems to be isotropic suggests that such states contribute little to $Be_A{}^8$ in the range of energies ($\sim$250 kv) investigated. This could then only be understood if the spacing of levels of different angular momentum in Be^8, even at the high excitation of 17 Mev, were still large compared to the very considerable breadth of these levels.

[14] Feenberg and Wigner, Phys. Rev. **51**, 95 (1937); Feenberg and Phillips, Phys. Rev. **51**, 597 (1937).

[15] Compare M. Goldhaber, Proc. Camb. Phil. Soc. **30**, 561 (1934).

[16] Kirchner, Physik. Zeits. **34**, 785 (1933); Giarratana and Brennecke, Phys. Rev. **49**, 35 (1936).

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Neutron Scattering Cross Section as a Function of Energy

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The study of scattering of neutrons of energy range from 0.02 to 80 volts from Fe, Ni, and Pb has been completed by measuring the activation of Ag, Rh, and CHI_3 detectors. The scattering of C neutrons was determined indirectly by two methods, and the results agreed closely. The scattering cross section for Ni fell off slowly with neutron velocity, that for Pb increased slightly, while that for Fe remained constant over the range from 0.02 to 80 volts. The directional distribution of neutrons emerging from the top of a paraffin cylinder containing a Ra–Be neutron source was investigated by placing detectors at various distances above the top of the paraffin. The results agreed well with those calculated for a cosine distribution law.

Part I. Scattering Cross Section

A CONSIDERABLE amount of work has been done recently on the scattering of neutrons from various materials. Mitchell and Murphy[1–2] measured the scattering cross section for a number of elements, while Pontecorvo and Wick[3] measured the reflection of neutrons from several substances and calculated scattering cross sections for a few of these. Furthermore, various materials sensitive to neutrons of different energies have been used as detectors. We have extended our experiments on the scattering of slow neutrons using various detectors and filter combinations so that we now have data on the scattering cross section of neutrons of energies from 0.02 to 80 volts for several different scattering materials.

The method used was that previously described with certain modifications which we shall show to be unessential. A cylindrical block of paraffin, 15 cm in diameter and 17 cm high, contained a source of neutrons located 6 cm from its top surface. Ag, Rh, and CHI_3 were used as detectors of the various groups of neutrons.

[1] A. C. G. Mitchell and E. J. Murphy, Phys. Rev. **48**, 653 (1935); Mitchell, Murphy, and Langer, Phys. Rev. **49**, 400 (1936).

[2] Mitchell, Murphy, and Whitaker, Phys. Rev. **50**, 133 (1936).

[3] B. Pontecorvo and G. C. Wick, Ricerca Scient. **1**, 134, 220 (1936).